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Schlieren photography is used to observe the steady state and transient behavior of axial and vectored flow in a two-dimensional thrust vector control nozzle in two different wind tunnels. It is shown that video recording in conjunction with a schlieren optical system is a convenient and useful means of observing transient flow conditions. To illustrate the video capability, the flow response in input variations in the two-dimensional confined jet nozzle is made visible and recorded by the schlieren/video system. The method can be used in wind tunnels in general.

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FLOW VISUALIZATION OF TRANSIENT PHENOMENA IN WIND TUNNELS

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ABSTRACT

Schlieren photography is used to observe the steady state and transient behavior of axial and vectored flow in a two-dimensional thrust vector control nozzle in two different wind tunnels. It is shown that video recording in conjunction with a schlieren optical system is a convenient and useful means of observing transient flow conditions. To illustrate the video capability, the flow response to input variations in the two-dimensional confined jet nozzle is made visible and recorded by the schlieren/video system. The method can be used in wind tunnels in general.

INTRODUCTION

Many types of thrust-producing nozzles are used in propulsion systems. An important element in these systems is thrust vector control (TVC) of the nozzle flow (1-4). Typical methods of TVC include the use of aerodynamic fins, vernier jets, jet vanes, hinged or gimballed nozzles, intermittent jets, and secondary fluid injection (1). However, in many of these TVC systems vector angles are less than 10 deg. Recent studies (4-7) of confined jet thrust vector control (CJTVC) nozzles have shown that vector angles as large as 30 deg can be obtained, but the vector angles are dependent on nozzle geometry and pressure ratios.

A typical CJTVC nozzle is shown in Figure 1. A CJTVC nozzle has a reconverging region and an exit orifice downstream of the diverging region. The nozzle operates with a reservoir-to-ambient pressure ratio that leads to an overexpanded supersonic primary flow in the diverging region. As shown in Figure 1, secondary injection through a port just downstream of the throat can cause the primary jet to separate from one side of the nozzle and attach to the other side. Without secondary injection the primary jet should separate uniformly in the diverging region and exit the nozzle in an axial direction. The symmetrical jet separation in this case will lead to symmetrical separation regions. Under vectored conditions, an asymmetrical separation in the nozzle is obtained, as illustrated in Figure 1. The pressure in the confined region may be higher than ambient, since the exit orifice tends to isolate the jet separation region from ambient conditions.

A number of studies have been conducted on CJTVC nozzles. Fitzgerald and Kampe (4) demonstrated the feasibility of the confined jet/vectoring concept and suggested the suitability of CJTVC for various applications. Other studies (5-7) have provided additional information and confirmed the concept. Three of the studies just cited relate to axisymmetric nozzles and one is for a two-dimensional nozzle configuration. While the performance characteristics of the axisymmetric nozzles have been determined, for example, in terms of axial thrust, side force, vector angle, and flow and pressure requirements for vectoring, the exact flow characteristics within the nozzle are not well known. By studying a two-dimensional version of a CJTVC nozzle, it is possible to observe the flow in the nozzle through schlieren photography. The study reported herein is an extension of the two-dimensional study of Talda and Franke (7).

The overall purpose of this study was to design and test a two-dimensional version of the CJTVC nozzle and visualize the flow separation and attachment under various vectored and non-vectored operating conditions. In particular, the purpose was to develop a special video recording method to obtain schlieren images from which steady and transient flow conditions in a two-dimensional CJTVC nozzle could be observed and recorded on tape.

TEST MODEL AND WIND TUNNELS

The configurations of the two-dimensional CJTVC nozzle chosen for this study were

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based on the work reported by Talda and Franke (7). A basic design model that had consistently demonstrated vectoring capability when discharging to ambient pressure was selected, but this nozzle had only been tested up to a nozzle pressure ratio (the ratio of primary flow total pressure to ambient static pressure) of approximately 15. Typical solid rockets have nozzle pressure ratios ranging from 50 to 1000 (8). Therefore, it was desired to test the nozzle at pressure ratios higher than 15. For safety and convenience this was accomplished by testing in a blowdown wind tunnel in which the ambient back pressure was reduced to increase the nozzle pressure ratios without increasing the primary total pressure. One-third scale versions of the original design were used to reduce the primary mass flow rate through the nozzle and thereby reduce the evacuation requirements of the blowdown wind tunnel. The one-third scale basic nozzle design and dimensions are shown in Figure 2. Plexiglas side plates were used so that the flow within the nozzle could be observed with the schlieren system.

The blowdown wind tunnel is a Mach 6 facility with up to 30 sec test time. The required pressure differential across the test section is provided by a compressed air system on the high-pressure side and a vacuum system on the low-pressure side. The test time is limited because of the capacity of the 15 m^3 vacuum chamber and the vacuum pumps. Reducing the flow area through the test section increases the test time.

A second wind tunnel used for this study was the S-1 Supersonic/Transonic wind tunnel located at the von Karman Institute for Fluid Dynamics (VKI), Rhode-St-Genese, Belgium. This tunnel is a continuous closed circuit facility driven by a 615 kW axial flow compressor. The test section is 40 cm x 40 cm. The tunnel is equipped with a high quality mirror schlieren system that is permanently mounted in the facility. Electric servomotors are used to adjust the image plane and knife edge.

SCHLIEREN OPTICAL SYSTEM

Schlieren optical systems have been used to visualize gaseous flow for many years (9-13) and have the advantage that they do not interfere with the flow. A typical schlieren system consists of a light source, two lenses, a knife edge, and a screen. Light from the source is collimated by a lens and passes through the test section. The light is then focused by another lens and projected on a screen or photographic plate. The theory of operation is based on the fact that the speed of light varies inversely with the index of refraction, which in turn, in a gas, depends on density. Thus, a ray of light passing through a transparent medium is refracted by density variations in the medium. A knife edge is used to exploit this refraction of light to produce photographic images with dark and bright areas depending on the density gradients in the flow field and the orientation of the knife edge. The knife edge is adjusted typically to intercept about half of the light at the focal point. Light rays passing through the density gradients normal to the light direction are deflected below or above the knife edge, thus giving a picture of density variations in the field in terms of shadow and highlight (12,13).

Generally, for cost considerations two concave spherical mirrors are used rather than two lenses. A typical configuration with mirrors is shown in Figure 3. Numerous applications of this configuration have been used in wind tunnel testing. Light sources are usually either steady mercury-vapor lamps or intermittent arc lamps.

SCHLIEREN PROCEDURE

Schlieren photography was used to record both steady state and transient phenomena. Steady state pictures were taken using a spark lamp together with a polaroid camera. A video camera and a VHS video cassette recorder (VCR) were used to record transient flow phenomena. The video camera was focused on a frosted glass plate placed in the same location as the film holder for still photographs. A continuous light source was used in place of the spark lamp. The video camera output to the VCR was observed on a color video monitor. Using this monitor, the knife edge of the schlieren system was adjusted for maximum contrast during actual test recording. This is a distinct advantage over still schlieren photography, which requires time-consuming trial and error runs to obtain the best contrast.

RESULTS AND DISCUSSION

Schlieren photography was used to determine the switching characteristics from axial to vectored conditions and vice versa. The video recordings allow for real-time review of the transient flow phenomena, which still photographs will not show. To illustrate axial and vectored flow conditions, some typical steady-state schlieren photographs of the full-scale nozzle design (7) are shown in Figures 4 and 5, respectively. Without secondary flow, the flow was axial with uniform separation on the upper and lower walls of the nozzle, Figure 4. With secondary flow from the secondary injection port on the upper wall, the primary jet separated from the upper wall and attached to the lower wall, Figure 5. The schlieren photography shows that the flow characteristics are similar to those observed by Thompson (14-15) and Bollmeier and Franke (16) in bistable two-dimensional fluidic devices.

For the one-third scale nozzle, schlieren/video pictures confirmed that the nozzle was bistable for some nozzle pressure ratios when, without secondary injection, the primary flow ld attach itself to either the upper ower wall rather than flow axially. T ieo pictures also confirmed that it was possible to switch the flow from one wall to the other using secondary injection and that axial flow was also obtained using secondary injection from both the upper and the lower wall ports.

In general, the schlieren/video provided additional information beyond that found previously for the full-scale nozzle by Talda and Franke (7). For example, in the one-third scale nozzle the distance along the axis where the flow separated from the diverging walls was measured from enlarged schlieren photographs taken at increasing nozzle pressure ratios with no secondary flow. The proximity of the separation points to the secondary injection ports indicates that the presence of the ports, even without flow, may influence the separation and formation of oblique shocks in the nozzle. However, tests on the nozzle without secondary injection ports at nozzle pressure ratios up to 13, showed that the separation points and oblique shocks were similar to those found in the nozzle with ports. This indicates that an adverse pressure gradient was a factor in the separation as well. It was also found that the separation location occurred at a cross-sectional area that was equal to or smaller than the exit area of the nozzle. This may be a controlling factor in axial flow separation.

Symmetrical separation was also obtained when there was equal flow from both secondary ports. In this case, the separation and oblique shocks occurred as illustrated in Figure 6. The separation and oblique shocks in the one-third scale nozzle were similar to those shown in Figure 4 for the original nozzle, but, in this case, the separation occurred farther upstream of the secondary ports due to the secondary flow.

At higher nozzle pressure ratios, normal shocks due to increased overexpansion were clearly evident in the photographs. A sketch of a typical observed flow with normal shocks is shown in Figure 7. These shock conditions are typical for large overexpansion in a duct with boundary layer effects (13).

Figure 8 illustrates typical flow and shock structures observed in the videotapes for a vectored case. In the vectored case, the secondary flow raises the pressure near the injection point causing a differential pressure across the primary jet and flow turning which causes the flow to attach to the other side. The separation and oblique shocks found with the one-third scale nozzle were similar to those shown in Figure 5 for the original nozzle.

While still photographs illustrate both axial and vectored flow conditions, the nozzle transient phenomena are observed best with motion pictures and video recordings. A good example of this was the recording of the switching process when the secondary flow was turned on to vector the primary flow. Another good example occurred when vortices were observed after a failure in the primary flow supply dryer allowed some water droplets to enter the nozzle. The water droplets traced a vortex path opposite the wall where the flow attached. Figure 9 is a sketch of the flow attachment and the vortex path observed on several occasions following start up of the primary flow. The vortex path was initially observed on still photographs and appeared to be streaks of the fluid used to clean the nozzle walls between test runs. Use of the schlieren videotape proved that the vortex was actually induced as part of the start up and bias of the nozzle flow.

The entire start up process was so brief that recording it on still photographs would have been extremely difficult and time consuming. On the other hand, the VCR had a frame-by-frame review capability which allowed immediate step-by-step review of the start up process that would not have been possible without the videotapes. A possible mechanism for the flow bias to the lower wall and vortex formation is illustrated in Figure 10. Two-dimensional vortex pairs have been shown to form when fluid is impulsively started through the sharp edges of a channel opening (17). Even with the video, it is not clear how the flow becomes biased to one wall causing the vortex on the attached wall to decrease in size and the opposite vortex to increase in size. There may be an initial asymmetry between the pair of vortices caused by a slight misalignment of the nozzle halves or an initial asymmetric flow disturbance. Further studies of this phenomena are needed.

CONCLUSIONS

This study has shown that video recording in conjunction with a schlieren system is a convenient and useful means of observing transient flow conditions. In this study transient flow and switching characteristics in a CJTVC nozzle were able to be recorded and studied. Video recordings provided valuable insight into the operating mechanisms of the CJTVC nozzle by illustrating shock formation, flow stability, and flow separation points. Videotaped schlieren images provide immediate real-time or extended-time review of both steady and transient phenomena in flow fields.

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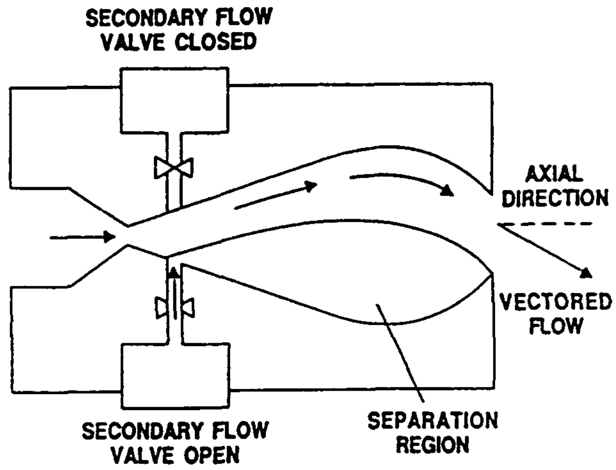

Figure 1. Vectored flow in a confined jet nozzle

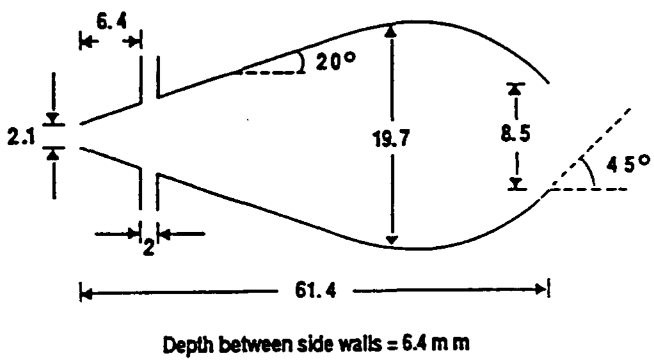

Figure 2. Nozzle dimensions in mm

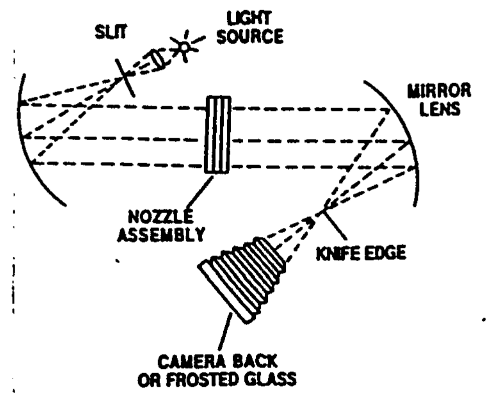

Figure 3. Schlieren configuration

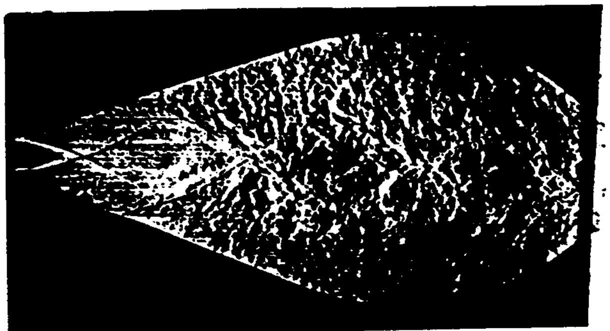

Figure 4. Schlieren photograph of axial flow (7)

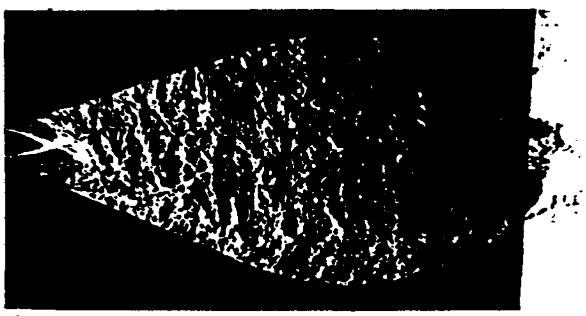

Figure 5. Schlieren photograph of vectored flow (7)

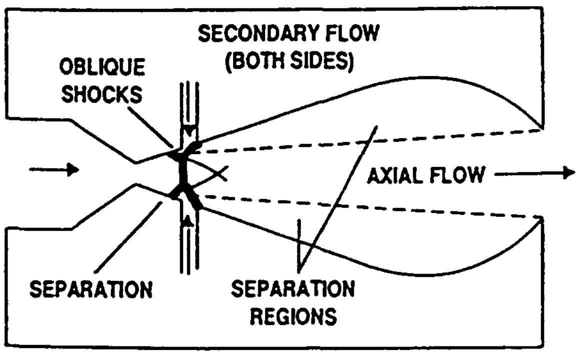

Figure 6. Axial flow with secondary flow from both sides

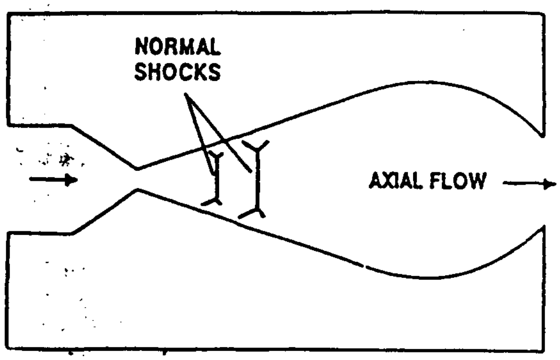

Figure 7. Normal shocks due to increased overexpansion

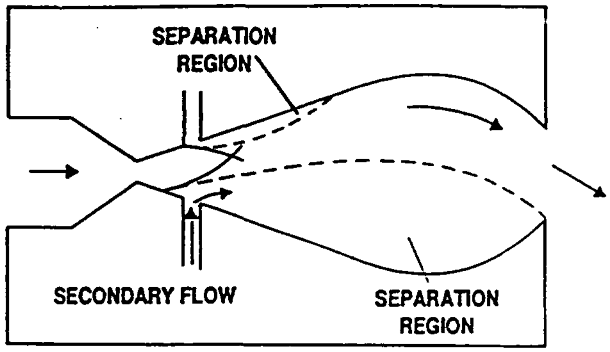

Figure 8. Vectored flow

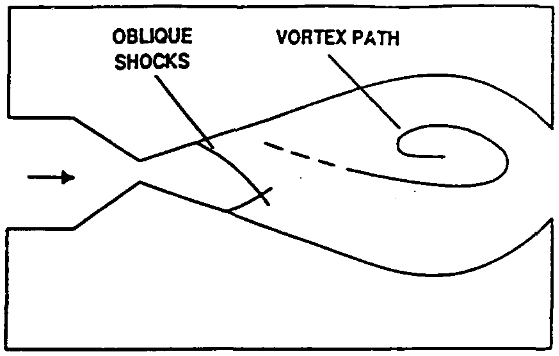

Figure 9. Flow attachment at start up

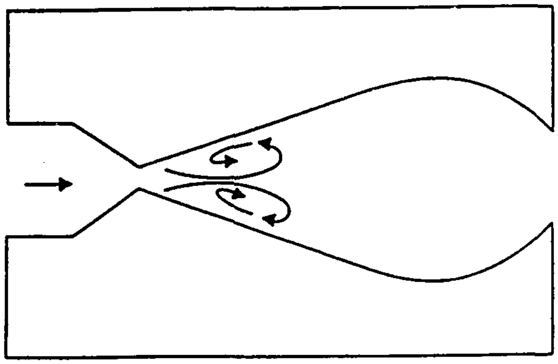

Figure 10. Initial vortex formation